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The gravitational wave 'probability event horizon' for double neutron star mergers

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ABSTRACT

Gravitational waves generated by the final merger of double neutron star (DNS) binary systems are a key target for the gravitational wave (GW) interferometric detectors, such as LIGO, and the next generation detectors, Advanced LIGO. The cumulative GW signal from DNS mergers in interferometric data will manifest as 'geometrical noise': a non-continuous stochastic background with a unique statistical signature dominated by the spatial and temporal distribution of the sources. Because geometrical noise is highly non-Gaussian, it could potentially be used to identify the presence of a stochastic GW background from DNS mergers. We demonstrate this by fitting to a simulated distribution of transients using a model for the DNS merger rate and idealized Gaussian detector noise. Using the cosmological 'probability event horizon' concept and recent bounds for the Galactic DNS merger rate, we calculate the evolution of the detectability of DNS mergers with observation time. For Advanced LIGO sensitivities and a detection threshold assuming optimal filtering, there is a 95% probability that a minimum of one DNS merger signal will be detectable from the ensemble of events comprising the stochastic background during 12–211 days of observation. For initial LIGO sensitivities, we identify an interesting regime where there is a 95% probability that at least one DNS merger with signal-to-noise ratio > unity will occur during 4–68 days of observation. We propose that there exists an intermediate detection regime with pre-filtered signal-noise-ratio less than unity, where the DNS merger rate is high enough that the geometrical signature could be identified in interferometer data.

Key words: gravitational waves – binaries: neutron stars – pulsars: general – supernovae.

1 INTRODUCTION

Three long-baseline laser interferometer GW detectors have been, or are nearly, constructed. The US LIGO (Laser Interferometer Gravitational-wave Observatory) has started observation with two 4-km arm detectors situated at Hanford, Washington, and Livingston, Louisiana; the Hanford detector also contains a 2-km interferometer. The Italian/French VIRGO project is commissioning a 3-km baseline instrument at Cascina, near Pisa. There are detectors being developed at Hannover (the German/British GEO project with a 600-m baseline, which had its first test runs in 2002) and near Perth (the Australian International Gravitational Observatory, AIGO, initially with an 80-m baseline). A detector at Tokyo (TAMA, 300-m baseline) has been in operation since 2001. The astrophysical detection rates are expected to be low for the current interferometers, such as 'Initial LIGO', but second-generation observatories with high optical power are in the early stages of development; these 'Advanced' interferometers have target sensitivities that are predicted to provide a practical detection rate.

Double neutron star (DNS) binary mergers are potentially among the strongest GW sources and are a key search target for interferometric observatories (Thorne & Cutler 2002). Eight close DNS binary systems are known to exist in the Galaxy as a subset of the observed radio binary pulsar population (Hulse & Taylor 1975; Wolszczan 1991). Energy loss from GW emission (Taylor & Weisberg 1989) causes an orbital in-spiral until the binary system coalesces, resulting in a burst of GWs usually described as a 'chirp' signal. The discovery of the DNS binary systems containing PSRs J0737–3039 (Burgay et al. 2003) and J1756−2251 (Faulkner et al. 2005) using the Parkes radio telescope brings the number of known DNS systems in the Galactic disk to merge within the Hubble time to four; this excludes the PSR B2127+11C system as it is in a globular

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cluster and probably not formed by binary evolution (see Table 1). With an orbital period of only 2.45 hr, the double pulsar system J0737–3039A,B will coalesce in only 87 Myr, a factor of 3.5 shorter than the coalescence time of the Hulse-Taylor PSR B1913+16 system, which yielded the first evidence for gravitational radiation. Predicted merger rates are dominated by the J0737–3039 system, because of its proximity, short coalescence time and the difficulty of its discovery (Faulkner et al. 2005). In contrast, PSR J1756–2251's parameters are similar to those of previously known pulsars; thus, its very recent addition isn't expected to significantly alter the predicted merger rate.

In order to estimate the DNS coalescence rate, Kalogera et al. (2001) used a semi-empirical approach, based on the physical properties of known DNS systems and pulsar survey selection effects, to obtain scale factors that correct for the unobserved fraction of existing systems. In an alternative approach, Kim et al. (2004) generated the probability distribution of merger rates using Monte Carlo simulations in which they populate a model galaxy with a specified number of NS binaries whose properties are those of known systems; they also model survey selection effects to deduce detection rates and their statistical significance. With this model and more up-to-date pulsar survey results that include J0737–3039, Kalogera et al. (2004) presented updated bounds for the coalescence rate for Galactic disk DNS systems, yielding $R_{\rm DNS} = 83^{+209.1}_{-66.1}$ Myr^{-1}, and derived detection rates for Initial and Advanced LIGO of $34.8^{+87.6}_{-27.7} \times 10^{-3}$ yr^{-1} and $168.8^{+470.5}_{-148.7}\times$ yr^{-1} respectively, factors 5–7 higher than previous estimates.

Others (Piran 1992; Ando 2004) assume a simple parametrization of merger rates with merger probability $P_m(t) \propto t^{\alpha}$, where t is the time from formation of the binary and α is a constant; the distribution of mergers as a function of time is simply given by the convolution of the star formation rate with the distribution $P_m(t)$. Regimbau et al. (2005), using numerical simulations, derive a probability distribution for DNS merger time, τ, of the form $P(\tau) = 0.087/\tau$, and find that mergers are possible between 2×10^5 yr and the age of the Universe. Using both evolutionary and statistical models, Regimbau et al. (2005) find a Galactic merger rate of 1.7×10^{-5} yr^{-1}, similar to the lower bound calculated by Kalogera et al. (2004).

A purely theoretical approach to estimate coalescence rates can be based on the predictions of population synthesis models that attempt to simulate the entire pulsar population (Lipunov et al. 1997; Belczynski et al. 2002). However, the size of the parameter space and associated uncertainties involved seriously limit this way of inferring merger rates. For instance, new theoretical models of merger formation can have considerable impact: Recent simulations by Chaurasia and Bailes (2005) show that significant kick velocities imparted to neutron stars at birth give rise to highly eccentric orbits resulting in accelerated orbital decay and greatly reduced lifetimes. Their work indicates that a non-negligible fraction of DNS systems could merge within times as short as 10 yrs. This implies that there could be a selection effect favouring the observation of those binary pulsar systems that coalesce over relatively long times.

Our interest is in the detection of a GW background generated by DNS merger events throughout the cosmos. As a starting point, we adopt the Galactic coalescence rates

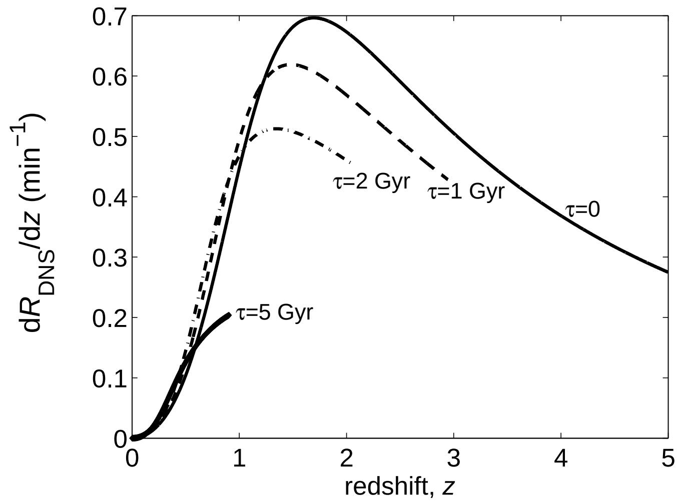

Figure 1. The differential DNS merger rate as a function of redshift z using the lower Galactic rate of 17 Myr^{-1} from Kalogera et al. (2004) and four merger times, τ = (0,1,2,5) Gyr, assumed the same for all systems. The curves are calculated using the SFR evolution factor obtained from the parametrized model labelled SF2 in Porciani & Madau (2001) and a flat-Λ cosmology with $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$, assuming a SFR cut-off at $z = 5$; the cut-off projects forward in time to the end points of the time-delayed curves. A time delay of 1–5 Gyr has minimal effect on $dR_{\rm DNS}/dz$ at small z compared to the differential rate locked to the evolving SFR.

of Kalogera et al. (2004) as a basis for estimating the rate density in our local intergalactic neighbourhood. To project this throughout the Universe, we assume that the DNS system formation rate follows the evolving star formation rate (SFR), for DNS systems with relatively short merger times of tens to hundreds of millions of years. In this way, we employ the updated Galactic DNS merger rate estimates as input to a model that describes the observer's evolving record of DNS mergers in terms of a 'probability event horizon' (PEH). We describe how the detectability of DNS mergers evolves with observation time.

We use the PEH concept (Coward & Burman 2005) to describe the cumulative GW signal from cosmic DNS mergers and show that the signal is dominated by the spatial and temporal distribution of events. Instead of describing such a signal as 'stochastic', we argue that the signal, although temporally random, has a unique signature. We use the term 'geometrical noise' to distinguish it from the stationary noise usually associated with a primordial GW stochastic background.

2 THE COSMOLOGICAL PROBABILITY EVENT HORIZON

In the standard Friedmann cosmologies, one can express the differential DNS merger rate as the merger rate in the redshift shell z to $z + dz$:

$$dR_{\rm DNS} = \frac{dV}{dz}\frac{r_0 e(z)}{1+z}dz\,, \tag{1}$$

where dV is the cosmology-dependent co-moving volume element and $R_{\rm DNS}(z)$ is the all-sky (4π solid angle) DNS merger

Table 1. DNS systems containing radio pulsars arranged in order of increasing estimated coalescence time. The first entry is the double pulsar system; the second system is in a globular cluster (M 15); the third is the Hulse-Taylor binary. Here, e is the orbital eccentricity, τ_c is the pulsar characteristic age and $\tau_{\rm GW}$ is the time remaining to coalescence due to emission of gravitational radiation. The relationship between a pulsar's characteristic and true ages is not clear, but we suppose the total coalescence time from birth to be $\tau_c + \tau_{\rm GW}$. Bold type indicates DNS systems that will coalesce in less than 10^{10} yr; the gobular-cluster system B2127+11C is excluded because its formation history is probably different from those of the Galactic-disk systems: it is likely that this system has undergone partner exchange from close interactions. References: (1) Lyne et al. (2004); (2) Burgay et al. (2003); (3) Anderson et al. (1990); (4) Hulse & Taylor (1975); (5) Faulkner et al. (2005); (6) Wolszczan (1990); (7) Lyne et al. (2000); (8) Nice et al. (1996); (9) Champion et al. (2004). Adapted from Faulkner et al. (2005)

PSR	pulsar period (ms)	orbital period (hr)	e	system mass ($M_\odot$)	τ_c (Myr)	$\tau_{\rm GW}$ (Myr)	Ref.
J0737−3039A,B	23, 2773	2.45	0.088	2.58	210,50	87	(1,2)
B2127+11C	31	8.04	0.681	2.71	969	220	(3)
B1913+16	59	7.75	0.617	2.83	108	310	(4)
J1756−2251	28	7.67	0.181	2.57	444	1690	(5)
B1534+12	38	10.10	0.274	2.75	248	2690	(6)
J1811−1736	104	449	0.828	2.6	900	1.7×10^6	(7)
J1518+4904	41	207	0.249	2.61	16,000	2.4×10^6	(8)
J1829+2456	41	28.2	0.139	2.5	–	6×10^4	(9)

rate, as observed in our local frame, for sources out to redshift z. Source rate density evolution is accounted for by the dimensionless evolution factor $e(z)$; this is normalized to unity in the present-epoch universe ($z = 0$) so r_0 is the $z = 0$ rate density. The Galactic DNS merger rate is converted to a rate per unit volume, r_0, using the conversion factor 10^{-2} from Ando (2004) for the number density of galaxies in units of Mpc^{-3}. The $(1 + z)$ factor accounts for the time dilation of the observed rate by cosmic expansion, converting a source-count equation to an event rate equation.

We assume a 'flat-Λ' cosmology, in which the density parameters of matter and vacuum energy sum to unity; we use $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$ for their present-epoch values and take $H_0 = 70$ km s^{-1} Mpc^{-1} for the Hubble parameter at $z = 0$. With the assumption that the DNS system formation rate follows the evolving star formation rate, $e(z)$ is obtained by normalizing a SFR evolution model to its $z = 0$ value. Presently there is no consensus among astronomers on a model of star formation history at high z, so we shall use the parametrized model labelled SF2 of Porciani & Madau (2001) scaled to the flat-Λ cosmology; see Coward & Burman (2005) for details. The cumulative DNS merger rate $R_{\rm DNS}(z)$ is calculated by integrating the differential rate from the present epoch to redshift z:

$$R_{\rm DNS}(z) = \int_0^z (\mathrm{d}R_{\rm DNS}/\mathrm{d}z)\,\mathrm{d}z\,. \tag{2}$$

Whereas core-collapse supernova events (because of their short-lived progenitors) closely follow the evolving star formation rate, DNS merger events are generally significantly delayed with respect to star formation. In order to test the sensitivity of $\mathrm{d}R_{\rm DNS}/\mathrm{d}z$ to this delay, we have calculated it under the simplified assumption that all such events are delayed by the same merger time τ. Figure 1 plots $\mathrm{d}R_{\rm DNS}/\mathrm{d}z$ for four choices of τ, namely 0, 1, 2 and 5 Gyr. The three delayed curves were obtained by converting $e(z)$ to a function of cosmic time (or, equivalently, look-back time), shifting it by τ and then converting back to a function of z. Cosmic time and z are related by the evolving Hubble parameter $H(z)$, which can be expressed in terms of the contributions of matter and vacuum energy (Peebles 1993):

$$h(z) \equiv H(z)/H_0 = \left[\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda\right]^{1/2} \tag{3}$$

for a flat-Λ cosmology, and cosmic time is expressed by the formula:

$$T_{\cos}(z) = \int_0^z [(1+z)h(z)]^{-1}\mathrm{d}z\,. \tag{4}$$

Figure 1 shows that a 1–2 Gyr merger time does not significantly alter $\mathrm{d}R_{\rm DNS}/\mathrm{d}z$, especially for small z. Increasing τ has the effect of reducing the available volume for observing DNS mergers and, for $\tau > 5$ Gyr, coalescences are restricted to the volume bounded by $z \approx 1$. So, for systems such as those used by Kalogera et al. (2004) in their rate estimates, we can safely assume that they quite closely follow the evolving star formation rate. For definiteness, in the following calculations, we assume that the DNS merger rate approximately follows the SFR evolution factor $e(z)$.

As the DNS mergers throughout the Universe are independent of each other, their distribution is a Poisson process in time: the probability ϵ for at least one event to occur in a volume out to redshift z during observation time T at a mean rate $R_{\rm DNS}(z)$ is given by an exponential distribution:

$$p(n \geqslant 1; R_{\rm DNS}(z), T) = 1 - e^{-R_{\rm DNS}(z)T} = \epsilon\,, \tag{5}$$

with mean number of events $N_\epsilon \equiv R_{\rm DNS}(z)T = |\ln(1-\epsilon)|$. The PEH is defined by the minimum distance, or redshift $z_\epsilon^{\rm PEH}$, for at least one event to occur over some observation time T, with probability above some selected threshold ϵ. We find $z_\epsilon^{\rm PEH}(T)$ by fixing ϵ and solving the above condition numerically, thus defining the PEH. In practice, we shall take

Table 2. The probability for at least one DNS merger to occur within the volume bounded by the luminosity distance $d_{\rm L} = 20$ Mpc for one year of observation (Initial LIGO) and by $d_{\rm L} = 200$ Mpc for one day (Advanced LIGO) assuming the Galactic DNS merger rate limits, $R_{\rm DNS}$, from Kalogera et al. (2004).

Galactic $R_{\rm DNS}$ ($\rm Myr^{-1}$)	$p(d_{\rm L} = 20$ Mpc; 1 yr) Initial LIGO	$p(d_{\rm L} = 200$ Mpc; 1 day) Advanced LIGO
292	0.13	0.86
17	0.008	0.11

$\epsilon = 0.95$, corresponding to a 95% probability of observing at least one event within z, so $N_\epsilon = 3$ is the mean number of events. Converting $z_\epsilon^{\rm PEH}(T)$ to luminosity distance $d_{{\rm L}\epsilon}^{\rm PEH}(T)$, and differentiating with respect to T then yields $v_\epsilon^{\rm PEH}(T)$: the PEH velocity, which describes the rate at which observations penetrate into the low-probability 'tail' of the event distribution.

Table 2 uses equation (5) to calculate the probability for at least one DNS merger to occur within the volume bounded by $d_{\rm L} = 20$ Mpc for one year of observation (Initial LIGO) and within $d_{\rm L} = 200$ Mpc for one day (Advanced LIGO) using the maximum and minimum values of the Galactic DNS merger rate $R_{\rm DNS}$ as estimated by Kalogera et al. (2004), namely 292 and 17 $\rm Myr^{-1}$. The two distances, 20 and 200 Mpc, correspond approximately to the detection thresholds for DNS merger detection for Initial and Advanced LIGO respectively. Figure 2 plots $d_{{\rm L}\epsilon}^{\rm PEH}(T)$, using the upper and lower Galactic merger rate limits from Kalogera et al. (2004).

3 THE PEH FOR LIGO TO DETECT DNS MERGERS

For a DNS merger at distance r from the detector, the optimal GW signal-to-noise ratio, ρ, assuming matched filtering is (Hughes 2002):

$$\rho = 11.7 \frac{|\Psi|^2}{2.56} \left(\frac{r_{\rm LIGO}}{r} \right) \qquad (6)$$

where $r_{\rm LIGO} = 20$ and 200 Mpc for Initial and Advanced LIGO respectively and $|\Psi|^2$, the angular sensitivity function of the detectors, averages to 2.56 over all sky and source positions. By substituting $d_{{\rm L}\epsilon}^{\rm PEH}(T)$ for r in equation (6), we obtain the DNS merger probability event horizon of the optimal signal-to-noise ratio:

$$\rho_\epsilon^{\rm PEH}(T) = 11.7 \frac{|\Psi|^2}{2.56} \left(\frac{r_{\rm LIGO}}{d_{{\rm L}\epsilon}^{\rm PEH}(T)} \right) . \qquad (7)$$

Assuming $\rho \sim 11.7$, corresponding to the detection threshold for a DNS merger in Advanced LIGO for an 'average' source at 200 Mpc (Hughes 2002), one can model the evolution of ρ as a function of duty cycle or observation time. Figure 3 plots $\rho_{0.95}^{\rm PEH}(T)$, showing the PEH for at least one DNS merger to occur during observation time T, with $\rho \geqslant \rho_{0.95}^{\rm PEH}(T)$, for the upper and lower uncertainty limits of the local DNS rate densities (Kalogera et al. 2004). For Advanced LIGO, at least one DNS merger with a $\rho > 11.7$ will be detectable using a matched filter every 12–211 days with a 95% probability. For initial LIGO sensitivities, events with the same ρ will be detectable at a rate of one per 22–380 yr and for $\rho \sim 1$, one every 4–68 days. Although DNS mergers with $\rho \lesssim 11.7$ will be present in the data, they are unlikely to be temporally resolved.

Here, we consider a signal comprised of an ensemble of chirp signals that result from the final mergers of cosmo-

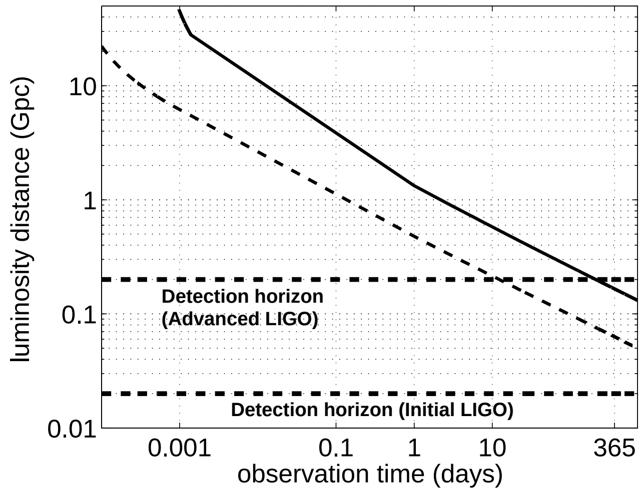

Figure 2. The PEH evolution for DNS mergers as a function of observation time assuming the Galactic merger rate limits from Kalogera et al. (2004): 292 $\rm Myr^{-1}$ (dashed curve) and 17 $\rm Myr^{-1}$ (solid line), and merger rate evolution following the instantaneous SFR. The horizontal lines show the 200 and 20 Mpc horizons, indicating the sensitivity limits for DNS coalescence detection assuming optimal filtering for Advanced and Initial LIGO.

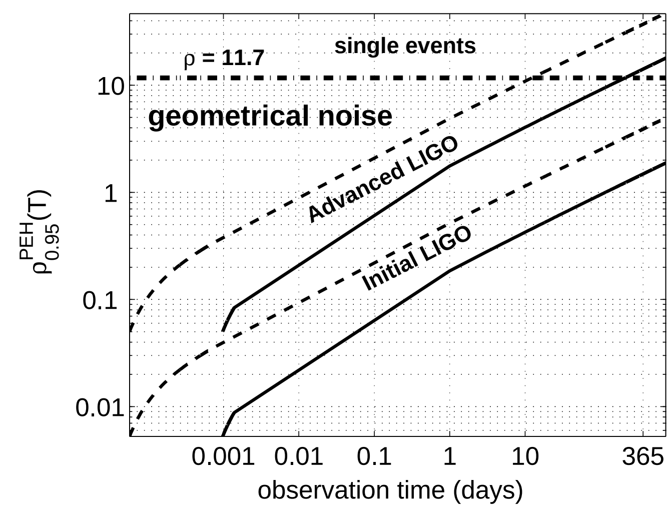

Figure 3. The 95% PEH for the temporal evolution of the signal-to-noise ratio $\rho_\epsilon^{\rm PEH}(T)$ for Advanced and Initial LIGO using the local Galactic rate limits for DNS mergers from Kalogera et al. (2004): 292 $\rm Myr^{-1}$ (dashed curve) and 17 $\rm Myr^{-1}$ (solid line). For Advanced LIGO with detection threshold $\rho > 11.7$ (assuming optimal filtering), at least one DNS merger will be detectable during 12–211 days of observation. For initial LIGO sensitivities, DNS mergers will be detectable in 22–380 yrs of observation and, for a $\rho \sim 1$, in 4–68 days. In the region below $\rho = 11.7$, individual mergers are unlikely to be detected, but the cumulative signal will manifest as 'geometrical noise' in interferometric data.

logical DNSs. Even though the individual signals will not overlap, the cumulative background is stochastic because one cannot predict with certainty the exact temporal evolution of the signal. But, the GW amplitude distribution will be very different from a continuous astrophysical GW background. For a signal that consists of a sum of many continuously emitting, randomly distributed sources, such as the GW signal from the Galactic population of white dwarf-white dwarf or white dwarf-NS binaries, the central limit theorem predicts that the GW amplitude distribution will be Gaussian. The term 'confusion noise' is often used to describe the signal from the Galactic population of white dwarf-white dwarf binaries. In contrast, the GW background from DNS mergers has a non-Gaussian signature that is characterized by the spatial distribution of the sources, so we use the term geometrical noise to describe it.

4 THE PEH TECHNIQUE APPLIED TO SIMULATED DATA

Coward, Burman & Blair (2002a,b) developed a procedure to simulate time series of the GW signals from supernovae occurring throughout the Universe. The method has provided a tool to probe the statistical signature of cosmological 'standard candle' GW sources that follow the evolving star formation rate. In its simplest form, the simulation outputs a distribution of events in redshift as a function of observation time. Here, we use this procedure to extract the PEH signature from a distribution of observer-source distances and observation times. The PEH technique is a procedure that records the time and distance of successively closer events, (t_i, r_i), that satisfy the condition $r_{i+1} < r_i$: each event in the PEH time series occurs at a shorter distance than the preceding one. A key feature of the procedure is that it probes the rate of an observer's penetration into the small probability 'tail' of an event distribution.

Coward & Burman (2005) applied this technique to the observed gamma-ray burst (GRB) redshift and observation-time distribution and found that it can be used to set limits on the local rate density of GRBs. Because it is sensitive to the distribution of events in the small probability tail, in this case corresponding to smaller volumes, the procedure 'tracks' the temporal evolution of close events as detected by an observer. If a time series is comprised of more than one class of event, then the PEH technique can identify these distributions based on the distribution of PEH data. This was shown by Coward & Burman (2005), where the PEH model fitted to the data indicated that the anomalously close GRB 980245 probably does not belong to the 'classical' GRB population.

As a further proof of concept, we apply the PEH technique to a distribution of GW amplitudes from a simulated distribution of DNS mergers throughout the Universe. We use a DNS dimensionless characteristic GW amplitude $h_c = 4\times10^{-21}$ at 20 Mpc (Schutz 1991) and a non-redshifted characteristic frequency $f_c = 200$ Hz. The results are plotted in figure 4. The 5% and 95% PEH curves are shown along with the output from the PEH simulation shown as data points. The 5% PEH curve is interpreted as the 'null PEH', as there is a 95% probability that no events will be observed at an amplitude above this threshold.

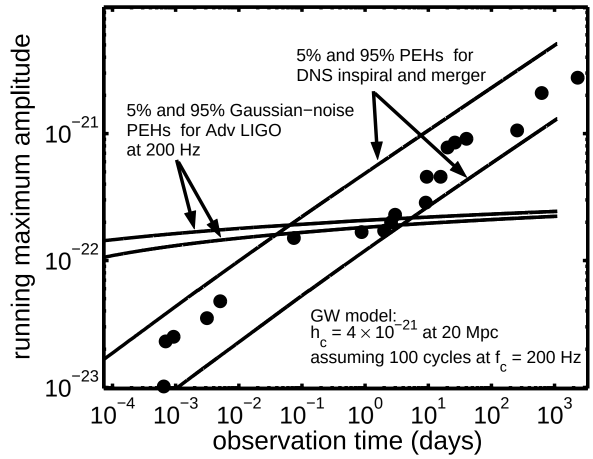

Figure 4. The PEH technique applied to a distribution of GW amplitudes from simulated DNS mergers throughout the Universe assuming the upper Galactic rate limit of 292 Myr^{-1} from Kalogera et al. (2004). We use a DNS characteristic GW amplitude $h_c = 4\times10^{-21}$ at 20 Mpc (Schutz 1991) and a non-redshifted characteristic frequency $f_c = 200$ Hz. The 5% (or 95% probability of no events occurring) and 95% PEH curves for DNS mergers are shown, along with the output of the PEH simulation applied to a distribution of characteristic GW amplitudes modelled on DNS mergers, shown as filled circles. Also shown are the 5% and 95% 'Gaussian-noise PEHs', modelled on idealized interferometric detector noise–see text for details. The figure shows that the DNS merger PEHs evolve much faster than the Gaussian-noise PEHs.

In order to develop the PEH concept into a technique for GW data analysis, we need to incorporate a method for treating detector noise. For 'standard candle' sources, this can be done by working in terms of progressively increasing amplitudes rather than progressively decreasing redshifts, as shown in figure 5. Noise transients of varying amplitudes mimic sources at varying redshifts, enabling the introduction of a 'noise PEH'. Here we use a 'Gaussian-noise PEH'; this is based on a standard zero-mean Gaussian distribution with standard deviation $s_d = h_{rms}\sqrt{f_s/2f_c}$, modelled on idealized interferometric detector noise with h_{rms} denoting the root-mean-square amplitude of the noise and f_s the sampling frequency–see Arnaud et al. (2003). Figure 5 shows the 5% and 95% Gaussian-noise PEHs.

It is clear from the small gradient of the Gaussian-noise PEH curves that the temporal evolution of transients, originating from the tail of the distribution is slow. The striking feature of this figure is the gradient of the PEH curves for the source amplitude distribution: it is much bigger than for the Gaussian-noise case, because of the distance-amplitude relation. We define this type of PEH data as 'geometrical', because it is linked to the spatial distribution of sources.

We note that although we have incorporated SFR evolution and a cosmological model to calculate the DNS merger rate at high z, the PEH will be most sensitive to events that are comparable to or greater than the detection threshold of the detector. For Advanced LIGO, this will be of order several hundred Mpc ($z \approx 0.05$), implying that the PEH will be dominated by sources in the local Universe where cosmological effects are minor.

Given that a geometrical signature is present in a time series, one can fit a PEH model to the data, with the local

rate density as a free parameter. In the presence of noise, this signature will be modified, but if the detector noise is well characterized, a fitting function constructed from the sum of both noise and geometrical distributions can be used. For small signal-noise ratios, the noise will dominate the PEH data for short observation times. But as observation time increases, the geometrical signature will grow at a faster rate than the noise. It is possible that the GW signal from DNS mergers can be identified before that of a single merger, occurring above the detector threshold, as shown in figure 3. We propose that there exists an intermediate detection regime, with pre-filtered signal-noise-ratio of less than unity, where the DNS merger rate is high enough that the geometrical signature could be identified in interferometer data. This type of search provides an opportunity to set upper limits on the DNS merger rate.

5 DISCUSSION

The cumulative signal from transient GW sources at cosmological distances is commonly described as a stochastic background because of the temporal randomness of the individual events. But we have shown here that, for a cosmic population of DNS mergers, the GW cumulative signal will be dominated by the spatial distribution and temporal evolution of the sources. We use the term 'geometrical' noise, because the GW amplitude distribution composed of DNS mergers is dominated by the spatial distribution of the sources.

Interestingly, geometrical noise from cosmic DNS mergers (and similar transient GW sources) is linked to the sensitivity of the detector and the cumulative event rate. If a GW detector could probe DNS mergers to distances corresponding to the time when they first occurred in the Universe, the detector could potentially resolve all events and there would be no geometrical noise from unresolved signals. However, if the cumulative rate measured in our frame were to be so high that the individual chirps would overlap, corresponding to a signal of duty cycle greater than unity, then the resulting signals would manifest as geometrical noise. This is unlikely for DNS mergers: the individual events are not expected to overlap but to be nonetheless not individually detectable because of the small signal-to-noise ratio.

We highlight the concept that the detectability of a GW stochastic background from DNS mergers throughout the Universe and of individual DNS mergers is linked to the observer via the instrument duty cycle, the cumulative event rate and the sensitivity of the detector. The PEH model is applied above to the detectability of DNS mergers with Advanced and Initial LIGO; it shows the temporal evolution of the GW signal from many faint unresolved events converging to detectable single events of high signal-to-noise ratio. Detection strategies based on the PEH model could utilize the geometrical signature of the temporal evolution of the chirp GW amplitude distribution. We plan to investigate the PEH technique further using simulated GW background and non-Gaussian noise data.

The PEH method could also be used to set constraints on the black hole-black hole (BH-BH) merger rate, which is presently highly uncertain. Although occurring at a lower intrinsic rate than DNS mergers, the GW emission from BH-BH mergers is expected to be significantly higher, implying an enhanced detection rate because of the larger detection volume. Estimates range from 30–4000 yr^{-1} assuming a BH mass of 10 $M_\odot$ and a detection horizon of $z = 0.4$ (Thorne & Cutler 2002) for Advanced LIGO sensitivity. We plan to use the BH-BH mass and merger rate distributions to determine if a PEH model could be developed and applied to interferometer data to set limits on the rate and mass distributions.

Although we have shown how the cumulative GW signal from DNS mergers should manifest in a time series, we have not yet tested how robust the above procedure is to the non-stationarity of the data. For instance, if a time series is plagued with non-Gaussian transients, then the effectiveness of the fitting procedure will be reduced, unless a good model for the transients is available.

We assume optimal (matched) filtering can be applied to the candidate transients, but the filters that will be most effective will not be exactly matched to individual events. The 'norm' and 'mean' filters, although not optimal, should perform at a significant fraction of a matched filter for transients where the signal is not completely characterized (Arnaud et al. 2003). We emphasize that using the PEH in a signal processing context is based on fitting to outliers using a model distribution and not 'detecting' individual events. Nonetheless, it is important to filter the data to select as many transients that are candidates for DNS mergers as possible. As a test of the robustness of the procedure using different filters, we plan to inject simulated cosmologically distributed GW transients into non-Gaussian noise.

We note that the simulated GW amplitude distribution will be modified by the detector antenna pattern, which we have not included in our simulations, where we used the mean value. In applying a PEH model to real data, account must be taken of the modulation and distortion of the signal by detector characteristics and by both detector and environmental noise. We plan to extend the current simulations by incorporating such effects as part of a program to test the sensitivity of the PEH fitting procedure.

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